Accepted for publication by The Astrophysical Journal
Preprint typeset using LaTeX style emulateapj v. 14/09/00

A LARGE ATOMIC HYDROGEN SHELL IN THE OUTER GALAXY: SNR OR STELLAR WIND BUBBLE?

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Accepted for publication by The Astrophysical Journal

ABSTRACT

We report the detection of a ring like H I structure toward ℓ=90°.0, b=2°.8 with a velocity of $v_{LSR} = -99$ km s^{-1}. This velocity implies a distance of d=13 kpc, corresponding to a Galactocentric radius of R_{gal} = 15 kpc. The $\ell - v_{LSR}$ diagram implies an expansion velocity of $v_{exp} \simeq 15$ km s^{-1} for the shell. The structure has an oblate, irregular shell-like appearance which surrounds weak infrared emission as seen in the 60μm IRAS data. At a distance of 13 kpc the size of the object is about 110×220 pc and placed 500 pc above the Galactic plane with a mass of $10^5 M_{\odot}$. An expanding shell with such a high mass and diameter cannot be explained by a single supernova explosion or by a single stellar wind bubble. We interpret the structure as a relic of a distant stellar activity region powered by the joint action of strong stellar winds from early type stars and supernova explosions.

Subject headings: ISM: atoms – ISM:bubbles – H II regions– ISM: kinematics and dynamics – supernova remnants

1. INTRODUCTION

There is no generally accepted overall picture of the spiral arm structure in the Galaxy, although we do know that there are star forming regions beyond the Perseus arm (Wooden 1971; Sabbadin, Bianchini & Strafella 1986). The H II region BG 2107+49, for instance, is known to be at R_{gal}=14 kpc (Higgs et al. 1987) and Chromey (1979) found OB stars at Galactocentric radii of R_{gal}=15 to 25 kpc. Furthermore, Chini & Wink (1984) and Blitz, Fich & Stark (1982) reported H II regions at R_{gal} ∼18 kpc and Digel et al. (1994) found molecular clouds associated with Hα emission at R_{gal}=18 to 28 kpc, whose kinetic temperature was comparable to that of local star forming regions. One of the clouds they found, designated as Cloud 2, has a kinematic distance of R_{gal} ≃28 kpc (de Geus et al. 1993; Digel et al. 1994). Recently, Kobayashi & Tokunaga (2000) have observed young stellar objects associated with Cloud 2 and suggested a smaller Galactocentric distance (∼ 20 kpc). In addition recent data show that Cloud 2 is associated with a larger H I ring (Stil & Irwin 2001, GSH 138 − 01 − 94). These authors interpret this object as snowplowed material resulting from a single supernova (SN) event.

The optical disk of the Galaxy may extend as far as 20 kpc from the Galactic center. The atomic gas, on the other hand, extends to a much greater radius; R_{gal} ∼30 kpc. Detection of star forming and H II regions beyond the optical disk provides information about the composition of the Galactic disk. The presence of these H II regions could explain the ionization of the diffuse gas at these large distances and hence give the extent of the magnetoionic medium in the Galaxy. At these distances the only possible objects which may be linked to the observed ionized gas are stars; because the general interstellar radiation field is weaker, metallicity is lower (Shaver et al. 1983; Fich & Silkey 1991) and there is less cosmic ray flux (Bloemen et al. 1984).

H II regions far from the Galactic center are in fact a common phenomenon in spiral galaxies similar to the Milky Way. Ferguson et al. (1998) have detected Hα emission from star forming regions in the extreme outer regions of the three nearby late-type spiral galaxies, NGC 628, NGC 1058 and NGC 6946. Leliévre & Roy (2000) identified 137 HII regions beyond a radius of ∼ 16 kpc with narrow-band Hα imaging in the galaxy NGC 628. M31 also has stellar activity in its outer disk; Cuillandre et al. (2001) found a population of B stars correlated with the extended H I distribution of M31.

With the increasing distance from the Sun, the spatial resolution of the telescopes decreases. While single-antenna data can be used to probe the H I cloud concentrations (Digel et al. 1994), to resolve these structures high resolution data are required. The new data at ∼ 1 arcminute resolution provided by the Canadian Galactic Plane Survey (Taylor et al. 2002, CGPS) are well suited to study the structure and dynamics of H I regions at the edge of and even beyond the optical disk. Such a structure detected serendipitously south of the SNR HB 21 in the CGPS database is the topic of this paper. This paper makes an attempt to clarify the possible origin of such large H I structures far from the Galactic center. We analyze the H I spectral line data together with the available continuum data at 1420 MHz and infrared data to show that the detected structure is the result of joint action of strong winds from early type stars and supernova (SN) explosions. We demonstrate that H I spectral line observations provide a very efficient method of tracing stellar activity at large distances from the Galactic center, but not many such structures have been detected because of the lack of data of sufficiently high resolution covering large areas.

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2. H I OBSERVATIONS

H I line observations were carried out with the Dominion Radio Astrophysical Observatory (DRAO) Synthesis Telescope (Landecker et al. 2000) as part of the CGPS. A detailed description of the data processing routines can be found in Willis (1999). The low spatial frequency HI data are from the Low Resolution DRAO Survey of the CGPS region observed with the DRAO 26-m Telescope (Higgs & Tapping 2000). Parameters relevant for the H I data are given in Table 1.

3. THE H I RING

We have detected an H I shell at $(\ell, b) = (90°, 2\overset{\circ}{.}8)$ in the H I survey data of the CGPS (see Fig. 1 and 2). A shell-like structure appears in the foreground Perseus arm gas at about $v_{LSR} = -90$ km s^{-1}. It slowly expands and gets more prominent with higher negative velocities. It is best pronounced at a velocity of $v_{LSR} = -99$ km s^{-1}. At further negative velocities it becomes smaller and fainter until it disappears at about $v_{LSR} = -114$ km s^{-1}. We call this structure GSH $90 + 03 - 99$, in accordance with the current nomenclature for Galactic atomic shells.

The atomic hydrogen map integrated between $v_{LSR} = -94$ and -106 km s^{-1} is given in Fig. 3. The structure is about $0\overset{\circ}{.}5 \times 1°$ in size. The radial velocity of -99 km s^{-1} corresponds to a kinematic distance of 13 kpc, which would give our H I structure a linear size of 110×220 pc, in ℓ and b, according to a flat Galactic rotation curve with $R_\odot = 8.5$ kpc and $v_\odot = 220$ km s^{-1}. Toward the structure there is very faint 1420 MHz continuum and infrared emission. In Fig. 4 we display the longitude-velocity diagram of the structure. Behind the Perseus arm at the exact center of the detected H I structure we see a shell like feature moving toward us, while the receding part is buried in the Perseus arm gas at lower negative velocities. This structure extends up to $v_{LSR} = -114$ km s^{-1}. As a result the deduced expansion velocity of the H I ring is $v_{exp} \simeq 15$ km s^{-1}. The mass of the structure is about 10^5 $M_\odot$, which together with the expansion velocity gives a kinetic energy of 2.3×10^{50} erg currently in the expanding shell, comparable to the explosion energy of an SNR. However, at such a low expansion velocity the SNR should already be at the end of the radiative phase with most of its energy radiated away and therefore no longer "visible" in continuum emission.

The kinematic age of the observed shell $t = \alpha\ R/v_{\rm exp}$, with a mean radius $R = 80$ pc, would result in an age 1×10^6 yr for a radiative supernova remnant ($\alpha = 1/4$) and 3×10^6 yr for a supershell ($\alpha = 3/5$). For GSH 138−01−94, these values are 4×10^6 yr and 9×10^6 yr, respectively. Apparently the object is too old to be an SNR, which typically has an observable lifespan of 10^5 yr. This obtained age, on the other hand is young in comparison to the distant Galactic shells listed by Heiles (1984), which are $\sim 10^7$ yr old, have typical energies $(1 - 5) \times 10^{52}$ erg and are usually up to 10 times larger than the detected structure. Nevertheless, the object has a mass comparable to that of distant Galactic shells and yet a size comparable to that of local shells. For instance, the Local Bubble, North Polar Spur and Gum Nebula are just twice as large as this H I shell (Heiles 1998).

We have checked the region in the Columbia CO survey (Dame et al. 1987). There is no evidence of associated molecular material. However this survey has coarse angular resolution and is undersampled. Especially the area of interest has a low signal-to-noise ratio; a signal below 0.5 K could not be detected. The maximum molecular hydrogen column density would be $N_{H_2} \simeq 1.2 \times 10^{20}$ cm^{-2} per km s^{-1}. Assuming a molecular material distribution comparable to the atomic hydrogen distribution, a maximum molecular mass of $M \simeq 10^5\ M_\odot$ in the velocity interval, shown in Fig. 1, for instance, could stay undetected. Thus, non-detection in the Columbia data does not necessarily mean that there is no molecular gas in the region.

3.1. *Would it be possible to identify any related stars?*

H II regions are expected to include stars. However, stellar light suffers from absorption and reddening by the intervening material. Therefore, beyond a certain distance stars of an H II region cannot be observed.

At the north-western part of the structure there is the UV star Lan 110 (Lanning & Meakes 1994), at $\ell = 89\overset{\circ}{.}9$ and $b = 2\overset{\circ}{.}91$. We have calculated the H I absorption profile of a nearby extragalactic source at $(\ell, b) = (89\overset{\circ}{.}93, 3\overset{\circ}{.}05)$ and thereby found a foreground H I column density of 9.6×10^{21} cm^{-2}. Combining that with the observed optical parameters of the star results in a color of $(U - B)_0 = -1.85$. An O3 star would have $(U - B)_0 = -1.22$. Therefore, this UV star must be located in front of the Perseus arm rather than behind it. This star is apparently not related to the detected structure. This also demonstrates that the detection of stars within the structure would be difficult.

To clarify whether massive stars in the H I structure are observable, we have calculated extinction and reddening of typical O and early B type stars, based on the foreground H I column density and the distance. The measured foreground H I column density is 9.6×10^{21} cm^{-2}, which corresponds to a reddening of

$$E_{\rm B-V} = \frac{N_{HI}}{4.8 \times 10^{21} {\rm cm}^{-2}} = 2.0 \text{ mag.} \qquad (1)$$

as given by Bohlin, Savage & Drake (1978). This gives a visual extinction of $A_V = 6.4$ magnitude.

A typical, main-sequence O3 star has an absolute magnitude $M_V = -6.0$ and color indices $(B - V)_0 = -0.33$ and $(U - B)_0 = -1.22$. The above reddening and extinction in turn correspond to apparent visual magnitudes of $m_V = 16^{\rm m}$, $m_B = 17.7^{\rm m}$ and $m_U = 18^{\rm m}$.

For a main-sequence B1 star, with $M_V = -3.2$ and color indices $(B - V)_0 = -0.27$ and $(U - B)_0 = -0.95$, the above calculation yields visual magnitudes $m_V = 18.8^{\rm m}$, $m_B = 20.5^{\rm m}$ and $m_U = 21.2^{\rm m}$. We note that, for both O3 and B1 stars the observed color indices are $(B - V) > 0$ and $(U - B) > 0$. Lanning & Meakes (1994) have detected stars in the range from $(U - B) = 0$ to -1.5, and in magnitude from $m_U = 10^{\rm m}$ to $21^{\rm m}$ in this region. Therefore, stars with positive $(U - B)$, as those which were mentioned above, are missing in their list.

These calculations show that deep measurements have to be made in order to detect early type stars which may contribute to the energy budget of the H I ring by their stellar winds.

Near infrared measurements, on the other hand, might provide further hints about the existence of embedded,

young OB clusters inside the H I structure like those found in GSH $138-01-94$ (Kobayashi & Tokunaga 2000), since there exists an infrared source in the area enclosed by the H I shell (see Sect. 4). However, such sensitive near infrared data toward GSH $90+03-99$ are currently not available.

4. OTHER OBJECTS IN THE REGION

The infrared source IRAS 20565+5003 is located almost at the center of the H I structure. According to Bronfman, Nyman & May (1996) the flux ratios 25μm/12μm (>3.7) and 60μm/12μm (>19.3) indicate a compact H II region. The observed infrared intensities for our source (0.91, 3.50 and 31.57 Jy, at 12, 25 and 60 μm, respectively) make this source a strong candidate for an H II region. Rudolph et al. (1996) observed 10 IRAS point sources, at distances R_{gal} 15 to 18 kpc, with the VLA at 2 and 6 cm. They found the spectral indices of these sources are consistent with the optically thin free-free emission from H II regions, signaling stellar activity at large distances. The distance of IRAS 20565+5003 is unknown and we have only circumstantial evidence that it is located within the H I ring. Therefore an association between the two is not certain, although the positional coincidence is attractive and compelling. Other IRAS sources in the region are away from the HI structure or do not satisfy the required infrared ratio criteria.

The H II region BFS 4 at $(\ell, b) = 90.^\circ 32, +2.^\circ 67$ is also in the region. However, the observed radial velocity, 1.1 ± 0.5 km s^{-1} (Blitz, Fich & Stark 1982), of BFS 4 implies that it is a local object.

5. SNR OR OB ASSOCIATION?

The observed H I structure may be attributed to an old SNR, which has already cooled to temperatures where ionized hydrogen recombines and creates the observed H I shell. Assuming the structure is the result of such an event we can calculate the maximum radius of the SNR as a function of the explosion energy and the ambient density. The mass of the observed H I structure is about 10^5 M$_\odot$, comparable to a typical giant molecular cloud, assuming the gas is optically thin. Thus, we obtain $n_0 \simeq 2.0$ cm^{-3} before the structure was formed. Due to the high Galactocentric radius of the H I ring, we have to take the metallicity into account, because lower metallicity causes slower cooling, which in turn results in a lower energy loss rate. Hence in the outer Galaxy SNRs live longer. There are two recent publications dealing with the dynamics of SNRs at late stages of their evolution taking metallicity effects into account (Cioffi et al. 1988; Thornton et al. 1998), latter based on the central equations of the former. Both discuss the so-called radiative expansion or snowplow phase at the end of SNR evolution. This phase consists of two parts: the cooling dominated first part and later the merger with the interstellar medium. At the end of the first part the SNR is no longer distinguishable from the environment. Thus we adopt the radius at the end of the first part as the maximum observable radius of an SNR. Following Cioffi et al. (1988) the maximum radius is

$$R_{\rm merge} = 51.3\ E_0^{31/98}\ n_0^{-18/49} \zeta^{-5/98} \tag{2}$$

where E_0 is the explosion energy in units of 10^{51} erg, n_0 is the mean ambient particle density in cm^{-3}, and ζ is the metallicity normalized to the solar value.

Using this model we can estimate the energy required if the ring is the result of a single SN explosion. Since Eqn. 2 provides the maximum radius, the corresponding explosion energy will be a lower limit for the energy requirement. Results obtained from this calculation for GSH $90+03-99$ and GSH $138-01-94$, discovered by Stil & Irwin (2001), are given in Table 2.

In order to reduce the required explosion energy the SNR would have to be closer. We have calculated the mass of the structure from the observed hydrogen column density. Therefore it is proportional to the square of the distance, implying a linear dependence of n_0 on distance, d. Combining this with Eqn 2 we obtain $E_0 \propto d^2$. The maximum distance, $d_{\rm max}$, we would obtain for an explosion energy of 10^{51} erg is also given in Table 2.

Consequently, for the single SNR explanation the maximum distance of the structures, as calculated above put these objects significantly closer. The systemic velocities corresponding to the $d_{\rm max}$ values for these two objects lie between -20 and -40 km s^{-1} for GSH $90+03-99$ and -40 and -55 km s^{-1} for GSH $138-01-94$. These velocities, however, contradict the observed systemic values and require extremely high random motions never observed before. Therefore, we find such a close distance, hence a single SNR origin, for both of the objects *highly* unlikely. We should emphasize that all calculated values are extrema, making the single SNR hypothesis even more unlikely.

A single O type or an early B type star would create a stellar wind bubble of radius (McKee et al. 1984)

$$r_w = 56\ n_0^{-0.3}, \tag{3}$$

which in turn gives about 45 pc for the H I ring, with the above ambient density. The corresponding radius of a wind bubble for GSH $138-01-94$, is 83 pc. Therefore an association of several massive stars would be sufficient to form such bubbles. By comparing the SNR and wind-bubble calculations above, we conclude that a structure formed by a SN explosion and a stellar wind bubble would have comparable characteristics. Thus, the shells discussed in this paper could be formed by approximately equal numbers of SN explosions or winds of massive stars.

We find that a single SN event or a stellar wind bubble of a single massive star cannot be held responsible for the formation of such big structures. An OB association hidden within the structure, however, would create enough stellar wind power to carve such a region. Additionally, one must take into account the fact that these young stars will sometime become SN, contributing to the energy budget of the big H I structure. Stars are usually formed in groups and the creation of a single and yet massive star alone seems to be improbable.

We note that both of the H I structures discussed here have comparable characteristics. One exception is that GSH $138-01-94$ was first detected as an H I concentration from the Maryland-Green Bank Survey (Westerhout & Wendlandt 1982), later detected in CO emission (Digel et al. 1994). An early type B-star is reported to be associated with it (Muzzio & Rydgren 1974, "MR 1"). The radial velocity of MR 1 (Smartt, Dufton & Rolleston 1996, -90 ± 13 km s^{-1}) is comparable to the velocity of GSH $138-01-94$. Finally de Geus et al. (1993) and

Kobayashi & Tokunaga (2000) confirmed the existence of the ionizing star and classified the object as an H II region. Such associated objects are not known towards GSH $90+03-99$, since there are no such deep measurements. However its similarity to GSH $138-01-94$ strengthen the hypothesis that it contains stellar activity.

6. SUMMARY

We reported the detection of an expanding hydrogen shell (GSH $90+03-99$) most likely powered by a group of massive stars in its center. We interpret GSH $138-01-94$ recently discovered by Stil & Irwin (2001) as another example of a SN/OB-association powered bubble at a large distance. We think this is a common phenomenon and we expect the detection of similar objects in the future.

The size of GSH $90+03-99$ is $110{\times}220$ pc at a distance of 13 kpc. It contains 10^5 $M_\odot$ of neutral material and is expanding at 15 km s^{-1}. This gives a kinetic energy of 2.3×10^{50} erg. If OB associations are sufficiently distant, it becomes difficult to detect the optical emission from their members. In this case atomic and molecular gas are their best tracers and a survey with high angular resolution, covering a large area of the Galactic plane is ideal for their detection. Spectral information is decisive to distinguish the SNRs from H II regions; but at large distances, due to low surface brightness, this information is usually unavailable. Therefore, energetics of the observed structures become important to characterize these objects. H I, being unaffected by interstellar absorption, is an easily detectable tracer of objects at large distances, and is also very efficient for the study of their kinematics.

We thank Tom Landecker and Charles Kerton for careful reading of the manuscript and discussions. The Dominion Radio Astrophysical Observatory is a National Facility operated by the National Research Council. The Canadian Galactic Plane Survey is a Canadian project with international partners, and is supported by the Natural Sciences and Engineering Research Council (NSERC). This research made use of SIMBAD database.

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Table 1
Specifications of H I spectral line data

Parameter	Value
Polarization	Left and right circular
Bandwidth	1 MHz
Field size (to 20% response)	2.6 degree
Synthesized beam (EW×NS)	1× 1 arcmin
Velocity resolution	0.824 km s^{-1}
Total 256 Channel span	-158 to $+52$ km s^{-1}

Table 2
Characteristics of the two H I rings calculated from Eqn. 2. Here ζ is the ratio of metallicity to the solar value, $R_{\rm merge}$ is the maximum radius of a SNR before it disappears assuming the explosion energy is 10^{51} erg, E_0 is the explosion energy required when the observed radius of the object is equal to $R_{\rm merge}$, and $d_{\rm max}$ is the distance to the object if it is due to a single SNR with an explosion energy of 10^{51} erg.

Object	ζ	$R_{\rm merge}$ (pc)	E_0 (10^{51} erg)	$d_{\rm max}$ (kpc)
GSH $138-01-94$	0.1	93.3	8.0	5.9
	1.0	83.0	11.6	4.9
GSH $90+03-99$	0.1	44.7	6.3	5.2
	1.0	39.8	9.1	4.3

Fig. 1.— H I channel maps toward the H I shell. The contour represents the 1420 MHz radio continuum emission at 7.8 K T_B.

Fig. 2.— Same as Fig. 1 but for different radial velocities.

Fig. 3.— H I emission toward the detected ring of neutral hydrogen integrated between -94 and -106 km s^{-1}

Fig. 4.— Longitude–velocity diagram of the detected H I structure. The arrow marks the approaching shell.

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